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13. ABSTRACT *(Maximum 200 words)*

Space-time adaptive processing schemes effecting both equalization and interference cancellation for mobile narrowband digital communications under time-varying multipath conditions were developed. Interference cancellation was effected through the use of an "extended correlator" exploiting past symbol decisions to highly localize in time the contribution due to the desired signal. This facilitated a "dead" time zone during which the spatial correlation matrix of the interference could be estimated and used in an adaptive beamformer. Novel "sample-spaced" equalizer structures were developed based on the Zero-Forcing (ZF) criterion, the Minimum Mean Square Error (MMSE), and the Decision Feedback Equalization (DFE) criterion. For the case where (1) the delay spread is on the order of T, where 1/T is the symbol rate, as would be the case in voice communications,(2) at least two spatially separated or polarization diverse antennas are available at the receiver, and (3) each baseband antenna output is oversampled sampled by a factor of 3 or 4, we showed that equalization may be effected via either the ZF, MMSE, or DFE criteria via a small set of "sample-spaced" taps encompassing the delay spread which is a fraction of T. This is in contrast to conventional equalization which employs symbol-spaced taps encompassing roughly the duration of the pulse symbol waveform, which is on the order of 10T, for example. As a result, the new "sample- spaced" equalizers have an inherent capability to better track time-varying multipath channels than conventional equalization schemes,as evidenced by extensive computer-based simulations.

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AASERT 95: Blind Adaptive Beamforming For Mobile Communications

Final Technical Report

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1 Executive Summary of Research

This grant fully supported the dissertation research of AASERT student Timothy A. Thomas. A copy of his dissertation entitled "Space-Time Processing for Interference Cancellation and Equalization in Narrowband Digital Communications" is attached to this report. Dr. Thomas developed space-time signal processing algorithms for wireless digital communications that achieve the following objectives of the project related to establishing and maintaining a reliable military wireless digital communications link:

- **GOALS:**
  - equalize multipath effects for reliable communications
  - cancel jammers or co-channel interference
  - track rapid time-varying channels due to mobile platform

Further, the desire is to accomplish these goals under the following adverse conditions typical of a wireless multipath propagation communications environment as depicted in Figure 1.

- **ADVERSE CONDITIONS:**
  - small number of training symbols (e.g., 13 in results to follow)
  - low Signal-to-Noise Ratio (SNR)
  - strong jamming or co-channel interference

The successful achievement of these goals was faciliated by several key theoretical developments.

- **NOVEL THEORETICAL ATTRIBUTES:**
  - novel design of extended correlator and pseudo-noise training sequences for high time-localization of desired signal
  - use of approximation theory in conjunction with basis functions derived from known pulse symbol waveform of desired user
  - use of multirate digital signal processing

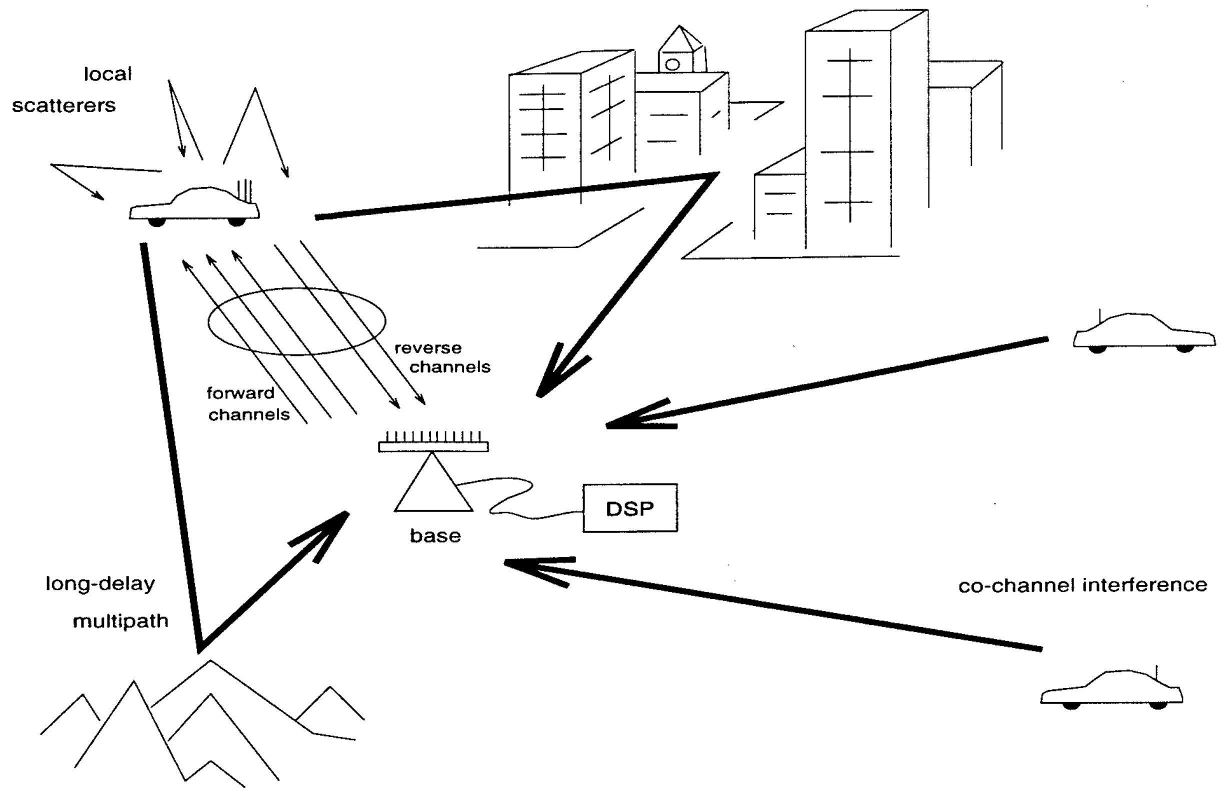


Figure 1. Typical outdoor RF wireless propagation environment.

Rapid Training to Effect Interference Cancellation and Equalization

To meet the first goal, we investigated the design of training symbols and, more importantly, novel schemes for processing the training segment of the received burst at each antenna to localize in time the contribution from the desired user's training signal and simultaneously achieve a gain against noise and interference. Innovation was needed since (1) the number of training symbols in a bursty TDMA format is typically quite small, 14 in the IS-136 standard, and (2) the nonnegligible tails of the pulse symbol waveform encompass many symbol periods. At each antenna, the training segment of the received burst is cross-correlated with a signal derived from the training signal. To counter the first problem, the "cross-correlating signal" is synthesized from a number of (symbol-spaced) sequence values greater than the number of training symbols, e.g., by a factor of 3, and the sequence values are not constrained to be members of the symbol alphabet. A procedure was developed for designing the extended correlator sequence so that its cross-correlation with the sequence of training symbols well approximates a Kronecker delta function. To counter the second problem, the result of this cross-correlation operation is passed through a sidelobe reducing filter based on the sidelobe reducing principle underlying raised cosine windows.

As a result of these operations, the contribution of the desired user's training signal to the extended correlator output is highly localized in time. Exploiting this feature, we developed schemes for forming interference canceling beams with mainlobes encompassing the angular spread of the desired user's multipath; NO direction finding is needed. Typical beam patterns synthesized under "stressful" urban wireless conditions based on the IS-136 based TDMA cellular standard are plotted in Figure 2(a). The mainlobes of the two beams are observed to encompass the angular spread of the desired user's

multipath. Further, each of the two beams is observed to have a deep null in the direction of each of the two interferers simulated in this illustrative example.

Exploiting both the spatial gain against noise achieved through this data assisted beamforming as well as the temporal gain against noise achieved by effectively adding the training symbols in phase, we developed schemes for estimating the impulse response of each beam channel via a small-order system of linear equations constructed from samples extracted from the center of the extended correlator output for each beam. The RF beam channel is not identified; we simply match the frequency response of the RF beam channel over the baseband bandwidth occupied by the raised cosine spectrum as shown in Figure 2(b). The red curves represent the magnitude of the frequency response of the beam channel associated with the beam pattern plotted in red in Figure 2(a). Similar comments hold with respect to the blue curves. The solid curve represents the actual beam channel while the dashed curve represents the estimate obtained from the procedure described above. For equalization purposes, it is only necessary to identify the frequency response of the channels over the baseband bandwidth occupied by the raised cosine spectrum demarcated by the dotted vertical lines in Figure 2(b).

The delay spread in the current US TDMA cellular system based on the IS-136 standard is on the order of the symbol time, i.e., the reciprocal of the symbol rate. Sampling each channel's output at roughly four times the symbol rate or less, we showed that under this condition equalization may be effected with sample-spaced taps at each beam encompassing a time duration roughly equal to the multipath time delay spread. The efficacy of this procedure is demonstrated by comparing Figures 2(c) and 2(d). A 16-QAM symbol alphabet was employed in this simulation example. The received constellation at a single antenna yields totally unreliable results due to both strong interference and intersymbol interference due to multipath. Figure 2(d) shows the result of zero-forcing equalization with sample-spaced taps as described above and illustrated in Figure 3. The equalized constellation is observed to be highly localized at 16 points as desired.

Decision-Directed Space-Time Equalization With Sample-Spaced Taps for Time-Varying Channels

For "post-training-signal" processing, novel multichannel equalizer structures were developed employing decision-directed updates of initial channel estimates formed from processing the short training sequence as described above. For the case where (1) the delay spread is on the order of T, where 1/T is the symbol rate, (2) at least two spatially separated antennas are available at the receiver, and (3) each baseband antenna output is oversampled sampled by a factor of 3 or 4, we showed that equalization may be effected via either the zero forcing, MMSE, or DFE criteria via a small set of "sample-spaced" taps encompassing the delay spread which is a fraction of T as assumed previously. For the DFE equalizer, the feed-forward filter is sample- spaced while the feedback filter is symbol-spaced. This is in contrast to conventional equalization which employs symbol-spaced taps encompassing roughly the duration of the pulse symbol waveform, which is on the order of 10T when the excess bandwidth parameter is less than 0.35, for example. The difference between symbol-spaced equalization with a single channel and sample-spaced equalization based on either the zero-forcing or the MMSE criteria is illustrated in Figure 3.

The comparative BER performance of the multichannel zero forcing, MMSE, and DFE equalizers

using sample-spaced taps is presented via an illustrative simulation example in Figure 4, along with the BER performance of the conventional multichannel symbol-spaced DFE, for the case where the channels vary substantially over the burst due to mobile motion. The new sample-spaced zero-forcing equalizer is observed to dramatically outperform the MMSE and DFE equalizers. This is due to the fact that the equalizer taps only span a fraction of a symbol time and thereby assume stationarity over a smaller time window than the DFE equalizers whose taps span a number of symbol times. This provides the sample-spaced zero-forcing equalizer with an inherent capability to better track time-varying multipath channels than conventional equalization schemes.

Tracking of an Evolving Interference Environment

Because the digital communications environment is very dynamic, interferers present at a beginning of a communications burst may not be present through the entire burst. New interferers may appear in the middle of the burst at different directions of arrival than the first set of interferers. There are a number of ways to handle this problem. The AASERT student developed two techniques for updating the beam weights to steer nulls toward "new" interferers and remove nulls torwards "old" interferers. The first employs a decision-directed version of the extended correlator approach described previously for the training signal.

The second method updates the weight vectors using an updated signal plus interference spatial correlation matrix, and the signal-only spatial correlation matrix derived from the training phase. It is assumed that the directions of arrival of the desired user's multipath do not change significantly over the burst. Since an estimate of the interference-alone spatial correlation matrix is not available via this method, the new interference cancelling beam weights are found indirectly. The procedure developed first finds weights that steer beams toward the interference and nulls toward the desired signal. These are then used to subsequently find beams that null out the interference and steer mainlobes toward the desired signal.

Simulations reveal the first technique to work well in tracking new interferers. The second technique requires the signal to be uncorrelated with the interference and therefore requires averaging over many symbol times (> 30) to get consistently good weight vectors that adapt to a new interference environment. However, the first method requires significantly more computation than the second method.

Figure 5 displays a typical simulation result comparing Method 1 and Method 2. The two initial interferers, interferers 1 and 2, came in at angles of $-50°$ and $60°$, respectively, at the same strength as the direct path of the desired signal. The first interferer turns off at symbol number 13, and the second turns off at symbol number 30. The two new interferers, interferers 3 and 4, arrive at $-30°$ and $40°$, respectively, at the same strength as the direct path of the desired signal. The new interferer at $-30°$ turns on at symbol number 19 and is on for the rest of the burst of symbols. The other new interferer turns on at symbol number 36 and is on for the rest of the burst of symbols.

Figure 5(a) shows that at symbol number 40, Method 1 yields a deep null in each of the two interferers that are turned on at symbol 30, interferers numbered 3 and 4. In contrast, the first beam yielded by Method 2 at symbol number 40 has sidelobes peaks at the angular locations of interferers numbered 3 and 4. This is particularly problematic since beam 1 contains most of the desired signals

energy. Note that the three centrally located vertical lines demarcate the arrival angles of the dominant multipaths of the desired user, which is where we desire the mainlobes to point towards.

These results indicate that for the purpose of rapidly steering nulls towards interferers in a dynamically evolving environment, it is better to create a "dead zone" where the desired signal strengh is negligible relative to strong interferers, through the use of the extended correlator concept, than to rely on the statistical independence amongst the different users. There is a very important result that we will well publicize.

Summary

The AASERT student, Timothy Thomas, developed space-time signal processing algorithms/architectures for wireless digital communications that simultaneously effect both equalization and interference cancellation. The algorithms have been tested extensively via simulation. Decision-directed adaptations of the training phase algorithms have been developed for adapting to rapid time-variations in the multipath and interference environments during the remainder of the communications link burst. Probability of bit error "waterfall curves" have been generated via extensive simulations for a variety of time-varying multipath propagation and interference environments.

The beam channel estimates obtained from the AASERT student's new identification and tracking schemes have been used to form various types of equalizers, including Decision Feedback Equalizers (DFE) and multichannel linear zero forcing equalizers. For these two primary classes of equalizers, the AASERT student has investigated the performance of symbol-spaced taps versus sample-spaced taps. The use of sample-spaced taps is a novel contribution; the simulations emphatically reveal that in a time-varying scenario the AASERT student's approach performs much better than that achieved with symbol-spaced taps in a frequency-selective environment.

The AASERT student has conducted extensive simulations to verify the efficacy of the overall space-time processor for equalization and interference cancellation. These simulations reveal the new approach to be highly promising. Initial simulations reveal that in just 13 symbols, the scheme can effectively cancel strong interferers as well as accurately equalize the desired signal in a fairly stressful multipath environment with a relatively low SNR.

The AASERT student presented various portions of this research at numerous very high-profile conferences sponsored by IEEE (Institute for Electrical and Electronics Engineering), which is the largest technical professional society in the world. Specifically, the AASERT student presented the following six papers which were well-received. Several journal papers assimilating all of this work are currently under preparation.

Peer-Reviewed Conference Papers Published.

1. T. A. Thomas and M. D. Zoltowski, "Nonparametric Interference Cancellation and Equalization for Narrowband TDMA Communications Via Space-Time Processing," *IEEE Signal Processing Advance in Wireless Communications Workshop - SPAWC '97,* Paris, France, 16-18 April 1997, pp. 185-188.

2. T. A. Thomas and M. D. Zoltowski, "Novel Receiver Signal Processing for Interference Can-

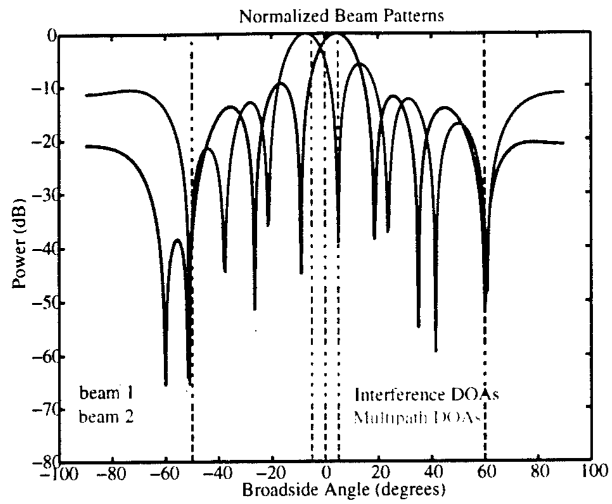
cellation and Equalization in Cellular TDMA Communications," *Proc. of the 1997 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing,* 21-24 April 1997, Munich, Germany, pp. 3881-3884.

3. T. A. Thomas and M. D. Zoltowski, "Novel Receiver Space-Time Processing for Interference Cancellation and Equalization in Narrowband TDMA Communications," *Proceedings of IEEE Vehicular Technology Conference (VTC) '97,* Phoenix, AZ, 4-7 May 1997, pp. 160-164.

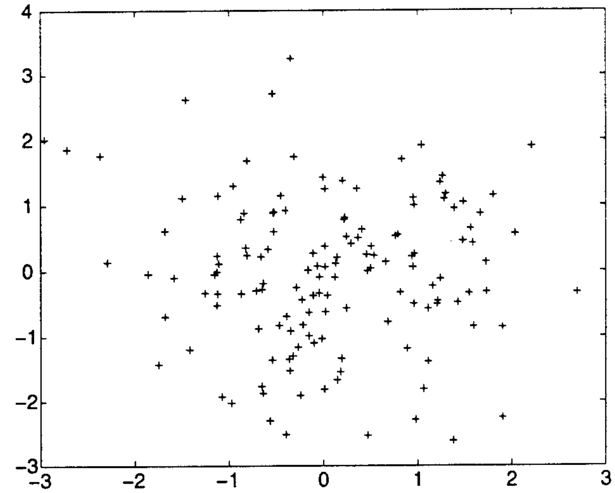
4. M. D. Zoltowski, D. Tseng, and T. A. Thomas, "On The Use of Basis Functions in Blind Equalization Based on Deterministic Least Squares," *invited paper, Conf. Record of the 31st Asilomar IEEE Conference on Signals, Systems, and Computers,* vol. 1, pp. 816-822, 30 Oct.-1 Nov. 1997.

5. M. D. Zoltowski and T A. Thomas, "Nonparametric Channel Identification, Interference Cancellation, and Multichannel Equalization for Narrowband Digital Communications," (invited paper) *Proceedings of Milcom '97,* Monterey, CA, vol. 3, pp. 1082-1086, 2-5 Nov. 1997.

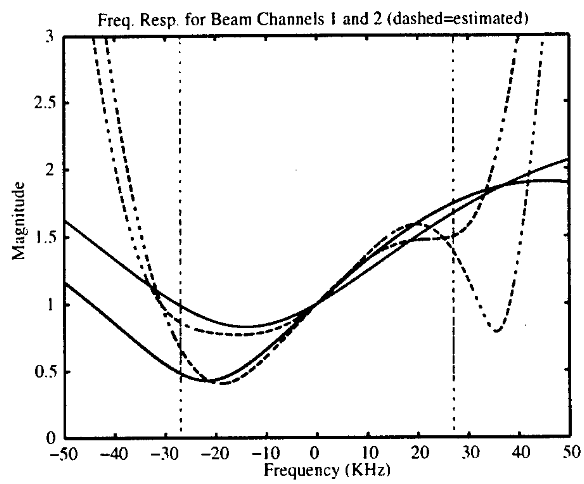
6. M. D. Zoltowski and T. A. Thomas, "Novel Zero-Forcing, MMSE, and DFE Equalizer Structures Employing Oversampling and Multiple Receiver Antennas," *invited paper,* to be presented at and included in *Conf. Record of the 32nd Asilomar IEEE Conference on Signals, Systems, and Computers,* 30 Oct.-1 Nov. 1998.



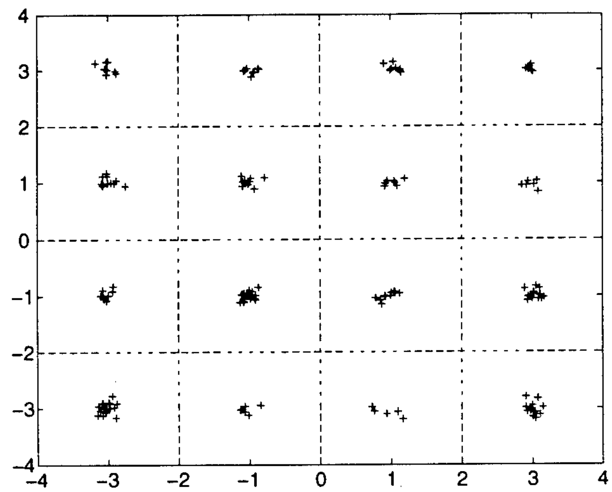
2(a). Beams formed with mainlobes encompassing desired signal's multipath and nulling interference



2(c). **BEFORE:** received constellation at single antenna



2(b). Frequency response of each beam channel accurately identified over communication band



2(d). **AFTER:** Equalized constellation obtained from oversampled beam outputs

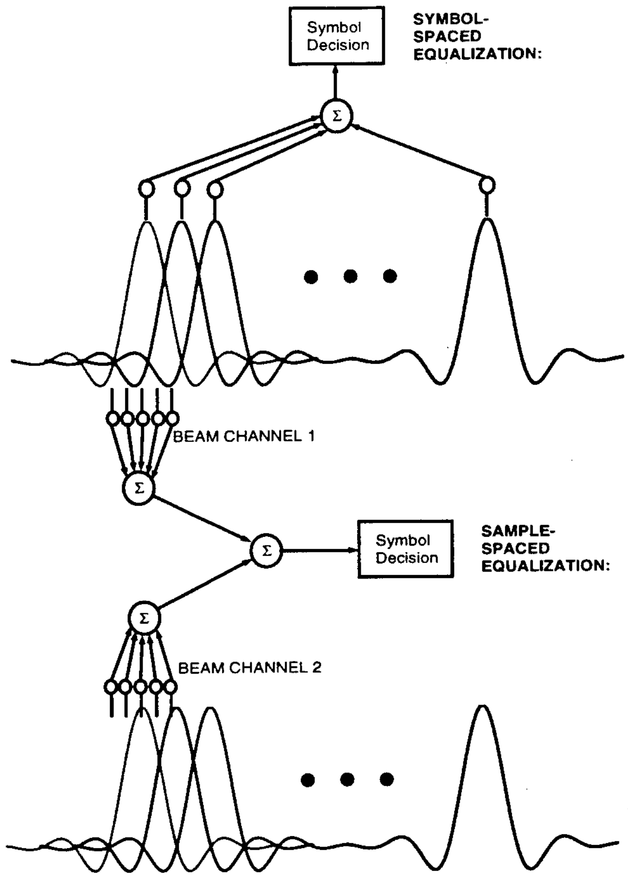
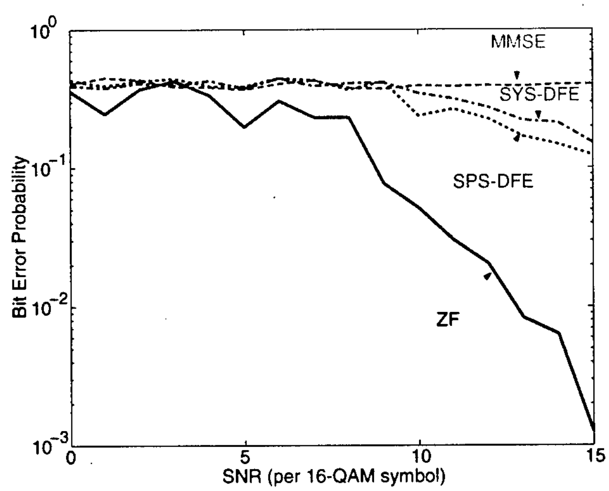


Figure 3. Sample-spaced versus NEW symbol-spaced equalization.

Mobile platform moves away from base at 65 mph
causing a distinct Doppler shift on each multipath arrival



MMSE: Sample-Spaced Feedforward Minimum Mean Square Error

SYS-DFE: Decision Feedback Equalizer - Symbol-Spaced Feedforward

SPS-DFE: Decision Feedback Equalizer - Sample-Spaced Feedforward

ZF: New Sample-Spaced Zero Forcing Equalizer

Figure 4. Dramatic improvement in bit error rate with new sample-spaced zero forcing equalizer.

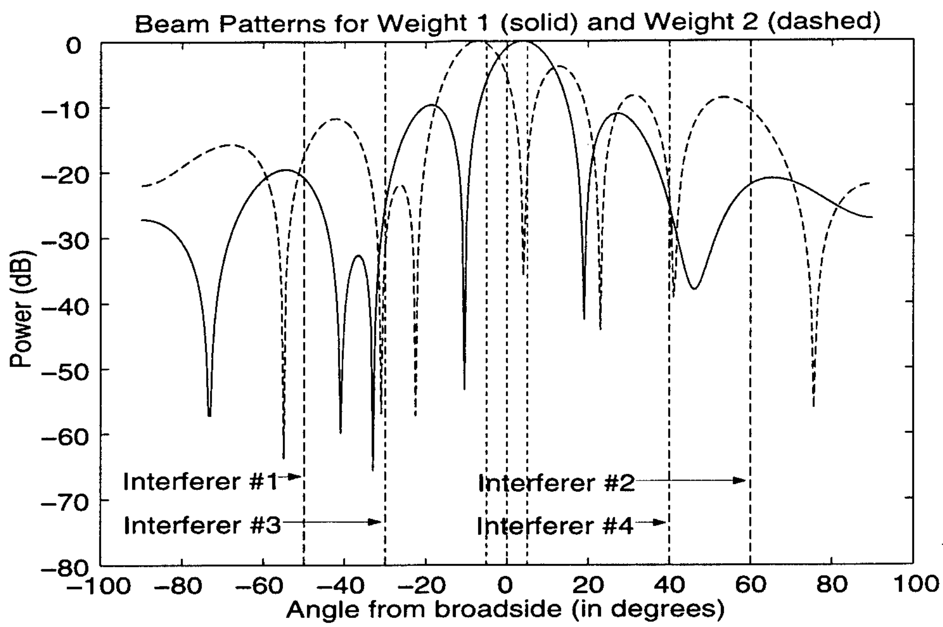


Figure 5(a). Beam weights at symbol 40 for Method 1 – interferers 3 and 4 on.

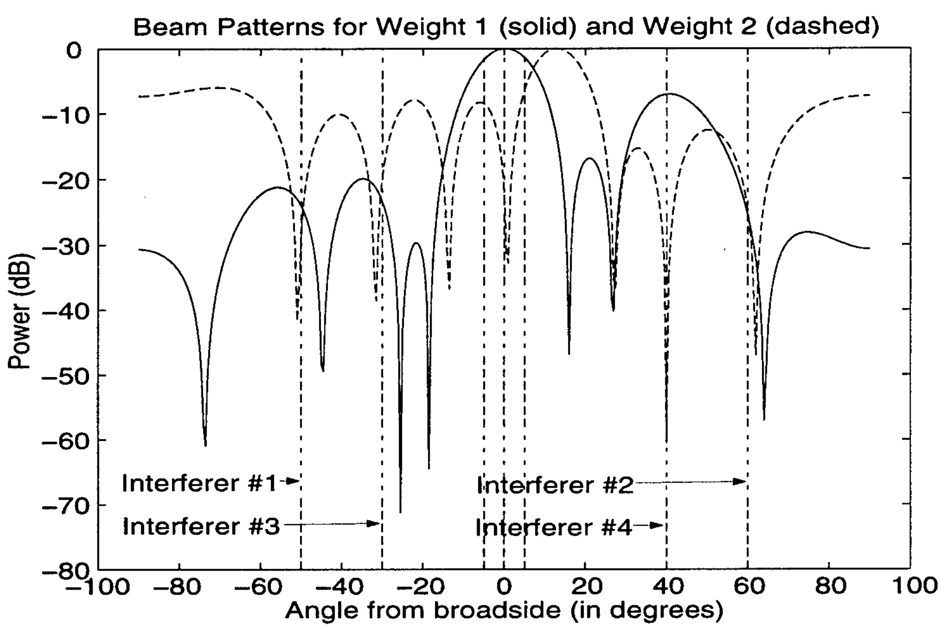


Figure 5(b). Beam weights at symbol 40 for Method 2 – interferers 3 and 4 on.